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Microwave measurement of complex permittivity of thin metal films

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In recent years there has been an increasing interest in the study of microwave properties of thin semi-metal and metal films (Gunn 1967, D'Aiello & Freedman 1969, Rainey *et al* 1970). The dielectric properties of these films are utilised in material characterization for the purpose of device fabrication and are helpful in the evaluation of useful free carrier parameters viz. mobility and relaxation time. Bismuth is a popular semi-metal, well known for its typical band structure and has evoked great interest in the past few years (Smith *et al* 1963, Williams & Smith 1964, Tripathi 1970). The microwave applications of thin metallic-films have also gained importance recently as exemplified by the use of films as microwave mirrors and as large size film reflectors (Korolev & Gridnev 1963). However, the microwave investigations of bismuth and metal films have received very little attention. Since the properties of thin films are quite different from those of the bulk, it is of interest to have measurements on films. It may be added here that the skin depth of these films is of the order of few microns for microwaves and hence microwaves would be best suited for the investigation of thin films.

We consider the propagation of electromagnetic waves in a rectangular waveguide in TE_{10} mode. Thin metal film is mounted along the axis of the waveguide and the length of the film is around 2 cm. The surface of the film is parallel to the narrow wall of the waveguide in much the same way as in an ordinary vane type attenuator.

For the portion of the waveguide loaded with the thin film, we can define a propagation constant, an expression for which may be obtained from our earlier paper (Dube & Natarajan 1973). The semi-metal film may be considered as a lossy dielectric with an effective dielectric constant defined as

$$\epsilon = \epsilon_L - \frac{4\pi i\sigma}{\omega} \qquad \ldots (1),$$

where ϵ_L is the lattice dielectric constant, σ is the complex conductivity and ω is the frequency of the wave. It may be mentioned here that eq (1) is justified

only when the dimension of interest (e.g. the thickness of the film) is greater than the Debye length (i.e. the screening length $\lambda_D = \frac{k_0 T \epsilon_L}{8\pi N e^2}$) k_0 is the Boltzmann constant, $-e$, N and T are the charge, concentration and temperature of electrons).

In a typical bismuth sample with electronic concentration $N \simeq 5\times10^{17}$/cc. the Debye length at room temperature is of the order of 100Å The films considered in the present investigation are thicker than the Debye length and hence can be treated as blocks of lossy dielectric. The boundary conditions of the continuity of tangential component of electric vector and its space derivative at the two faces of the sample are then justified and the propagation constant is governed by the same dispersion relation (Dube & Natarajan 1973)

It may be added here that the complex conductivity of the film may be expressed as

$$\sigma = \frac{Ne^2\tau}{m(\omega^2\tau^2+1)} \cdot (1-i\omega\tau) \qquad \ldots$$

where τ is the momentum relaxation time of carriers. For films under discussion, the film thickness is smaller than the bulk mean free path and hence the surface scattering of electrons is important. So far no analytical expression for τ due to surface scattering is available.

Thin bismuth, gold and aluminium films were prepared by the thermal evaporation of 99.99% pure material in a vacuum of about 10^{-6}mm Hg The films were deposited on to freshly cleaved mica substrates approximately 0.006 cm thick. Film thicknesses were measured utilising the frequency shifts of a crystal controlled oscillator (Chopra 1969).

The phase shift and attenuation for the samples were measured using the standard two channel bridge technique described earlier (Dube & Natarajan 1973). One arm of the microwave bridge contains the calibrated variable phase shifter and attenuator and the other contains the sample holder which is nearly 5 cm long waveguide having a sharply cut longitudinal slot at the center in the broad side dimension. The sample is introduced through this slot Proper care is taken for the films to have good contacts with the top and bottom sides of the waveguide walls. Adjustment of variable impedance to bring about null conditions at the detector end with and without the specimen measures the phase and attenuation introduced by the film. The components of permittivity are obtained using the values of phase constant and attenuation constant (Dube & Natarajan 1973)

In terms of an appropriate effective mass m^* and a relaxation time τ, the dielectric constant and conductivity of a metal film may be written as

$$\epsilon_r = \epsilon_L - \frac{Ne^2\tau^2}{\epsilon_0 m^*[1+(\omega\tau)^2]} \qquad \ldots (3)$$

$$\sigma = \frac{Ne^2\tau}{m^*[1+(\omega\tau)^2]} = \omega\epsilon_0\epsilon_i \qquad \ldots (4)$$

The lattice dielectric constant ϵ_L in the present case can be neglected as the electron contribution is highly dominant. Thus measured values of ϵ_r and ϵ_i can be used to evaluate the relaxation time from (3) and (4).

The experimental data for phase and attenuation constants for thin films of bismuth, gold and aluminium are shown in tables 1 to 3 The variations of phase and attenuation for bismuth films with thickness from 240 to 720 Å have been shown in figure 1

Table 1. Complex permittivity for thin bismuth films of various thickness. The measurements were taken at room temperature (312°K) and at a frequency of 9.410 GHz.

Thickness (Angstroms)	Phase shift/ Length (Degrees)	Attenuation/ Length (Decibels)	ϵ_r	ϵ_i
240	2 5	7·5 √	$0{\cdot}30\times10^5$	$3\ 12\times10^5$
360	12·0	10·8	$0{\cdot}91\times10^5$	$2\ 91\times10^5$
480	15·5	12·2	$0{\cdot}89\times10^5$	$2{\cdot}38\times10^5$
600	20·0	13·7	$0{\cdot}83\times10^5$	$1{\cdot}88\times10^5$
720	30·4	16·3	$1{\cdot}05\times10^5$	$1{\cdot}86\times10^5$

Table 2. Complex permittivity for thin gold films of various thicknesses. The measurements were taken at room temperature (310°K) and at a frequency of 9 410 GHz.

Thickness (Angstroms)	Phase shift/ Length (Degrees)	Attenuation/ Length (Decibles)	ϵ_r	ϵ_i
80	20·5	15·1	$7{\cdot}74\times10^5$	$1{\cdot}67\times10^6$
105	28·5	17 7	$7{\cdot}55\times10^5$	$1{\cdot}36\times10^6$
120	42·5	19·8	$8{\cdot}16\times10^5$	$1{\cdot}17\times10^6$
140	55·8	23·4	$7{\cdot}86\times10^5$	$1{\cdot}15\times10^6$

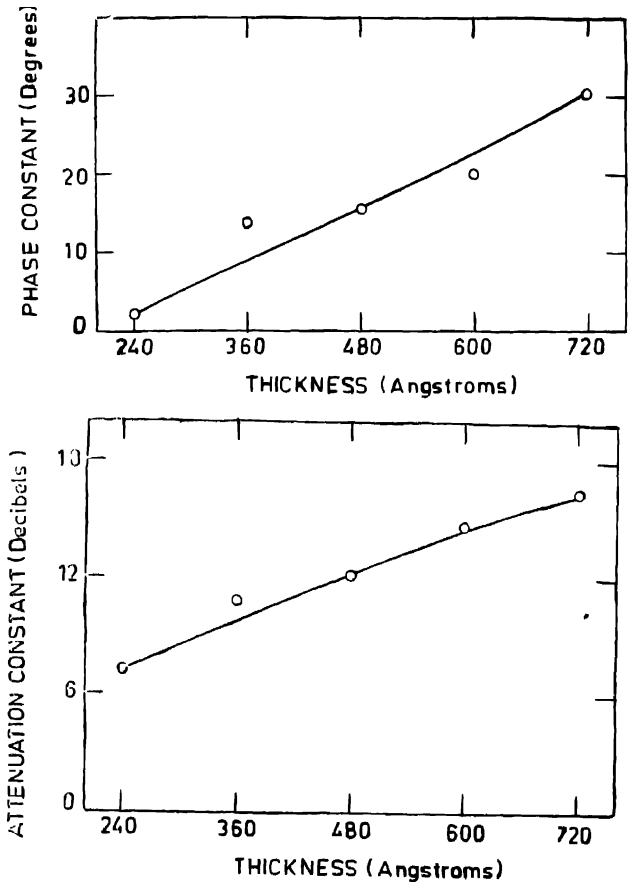

Fig 1. Variations of phase shift and attenuation with film thickness,

The high values of ϵ_r and ϵ_i as shown in the tables are due to free carrier effects in bismuth and in metal films The same order of magnitude of these parameters is obtained by substituting appropriate values for the quantities involved in eqs. 3 and 4 Variation of relaxation time τ with thickness for bismuth films is plotted in figure 2 The decrease in τ with the decrease in thickness may be attributed to surface scattering However, a quantitative treatment of this scattering is not available in literature.

Table 3. Complex permittivity for thin alluminium films of various thicknesses. The measurements were taken at room temeprature (310°K) and at a frequency of 9.410 GHz

Thickness (Angstroms)	Phase shift/ Length (Degrees)	Attenuation/ Length (Decibles)		
120	5·4	10·5	$2\cdot58\times10^{6}$	$7\cdot76\times10^{5}$
130	9·5	15·2	$4\cdot01\times10^{5}$	$12\cdot6\times10^{5}$
150	18·7	20·7	$5\cdot57\times10^{5}$	$10\cdot6\times10^{5}$
200	13·0	24·8	$5\cdot11\times10^{5}$	$8\cdot42\times10^{5}$

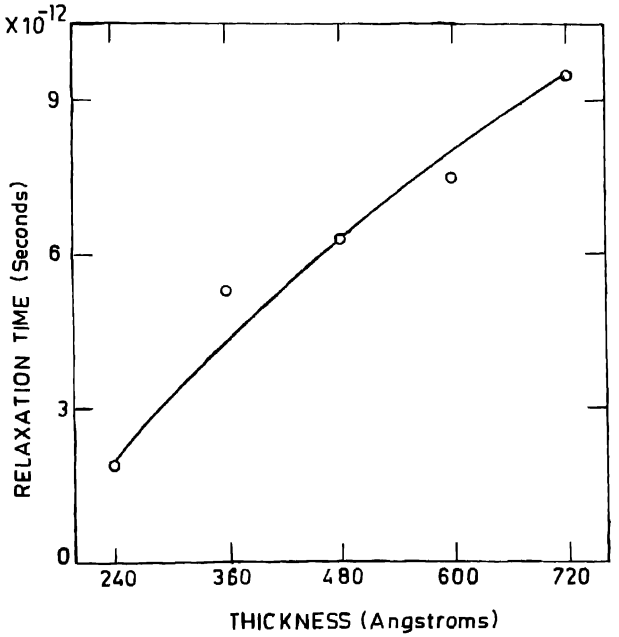

Fig 2 Variation of relaxation time with film thickness.

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